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Simulation-Assisted Management and Control Over Building Energy Efficiency – A Case Study

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Abstract

The specific aim of this research paper is to demonstrate how much energy use will be reduced if the simulation - assisted building energy management and control system is applied to a representative large office building. The methodology applied includes: (1) choosing an appropriate building simulation software to assess energy savings, (2) selecting a representative building and then creating the building model for simulation, (3) identifying the year with available weather data and actual building energy consumption data for the building selected, and then calibrating the simulation model using the actual building energy consumption, (4) selecting proper energy-saving strategies and applying them to obtain hourly energy use for a day. The optimal temperature schedule that saves the most energy was identified. Cost effectiveness studies were performed to evaluate how much annual energy saving has been achieved by using the management and control optimization strategy and how long it will pay back.

Keywords: Simulation-assisted control; Building energy management system ; Building energyeEfficiency

1. Introduction

Energy is the largest operating expense for both new and existing buildings. The building sector of the economy currently draws upon 40% of total energy use in the U.S. and is responsible for about 48% of all green house gas emissions annually [1]. It is clear that now is the time to make a commitment to building energy efficiency in the building sector to reduce energy cost and carbon dioxide emissions. The green industry has actually existed for more than 30 years. The Department of Energy (DOE) was formed after the first oil crisis in 1977 to research renewable energy and to improve energy efficiency. Both energy

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efficiency improvement and use of renewable energy are effective ways to reduce carbon footprints but building energy efficiency improvement has proven to be a much better monetary return[2]-[4].

Various BEMS have been developed and tested in buildings with either the prototype simulation-assisted control in BEMS [5], or using rule sets to make the intelligent decision support model in a typical BEMS [6], or incorporating BEMS data with the innovative intelligent decision support model to assess energy-saving measures in a typical building [7]. The research conducted by Cumali group[8] in 1988 is especially interesting. They applied the simulation-assisted building management and control systems to several actual buildings and among them, three large office buildings have achieved 20% electrical energy reduction. Nevertheless, in the past 20 years, significant progress has been made in improving building energy efficiency and the building codes have become more rigorous. As a result, modern buildings are better equipped with improved building/HAVC system components and reduced internal building loads. This raises a question on whether the same amount of saving will be achieved if the simulation-assisted building management and control systems are applied to a modern building. The primary objective of this research investigation is therefore to address this issue by demonstrating how much electrical energy savings will be achieved when the simulation-assisted building management and control systems are applied to a modern office building. The results will be compared with those of Cumali's.

2. Methods

For more than 30 years, building designers and research communities have used building energy simulation to design energy efficient buildings, assess energy savings from implementing energy efficient measures, and estimate the size of HVAC equipment. The DOE building simulation software was chosen for better fitting the current research in designing and retrofitting buildings although there are so many software options available in the market [9][10]. The DOE-2.2 software is composed of four subprograms as shown in Figure 1. The BDL Processor subprogram takes in the user's input files and accesses a library to generate the machine-readable BDL file. The simulation process then uses the BDL file and the local weather data to run the LOADS subprogram to calculate the hourly heating and cooling loads for the user-defined building model. Next, the SYSTEMS subprogram calculates the HVAC system loads to meet the set-point value of user-defined heating and cooling. Finally, the ECONOMICS subprogram calculates the hourly energy consumption and its cost. When the building simulation process is complete, the software, DOE-2.2 generates an Output Report [11].

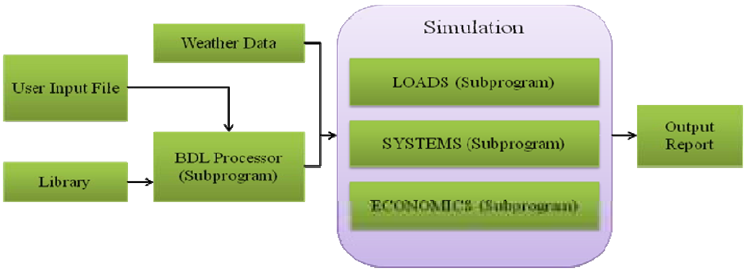

Fig.1. Flow Chart of DOE-2.2 Software Simulation

In order to demonstrate energy savings from simulation-assisted building management and control systems, a DOE-2.2 building model of an actual building has to be created. The actual building chosen here, as shown in Figure 2, is Legacy Civic Towers in San Jose, California, USA. It is a 14-story building with a basement, totaling up to 200,674 square feet. The reason to choose this building is that, it is a good representation of a typical high-rise office building in the San Jose area. The facility was built in 1997 and has participated in multiple PG&E commercial retrofit programs to keep the building efficiency up to date. The building is open from 6 a.m.to 6 p.m., Monday through Friday. For the last two years, the average building occupancy rate was at 60% of its maximum capacity. Another reason to select this building is that, both the weather data in 2007 from National Oceanic and Atmospheric Administration (NOAA) and the actual building energy consumption data from PG&E have been confirmed available.

Fig.2. Legacy Civic Towers [12]

In order to reflect the actual building use of energy, the computer model must be calibrated based on the actual energy consumption in the building. The calibration involved adjusting the occupancy rate, the plug-in equipment load, and other miscellaneous loads. The model was meant to calibrate to match within 10% of the actual billing data. By using the year 2007 weather data from National Oceanic and Atmospheric Administration (NOAA), the DOE-2.2 simulation of the building model was performed and the results were compared against the 2007 data with a 15-min kW interval from PG&E.

Figure 3 shows the comparison between the annual average hourly electric demand profile from the electric interval data and the simulation results. The hourly profile calibration calibrates building power demand for every hour. The simulation hourly profile has an average of 94% match to the actual building hourly profile, or the difference is 6%, which is within 10% of actual building data.

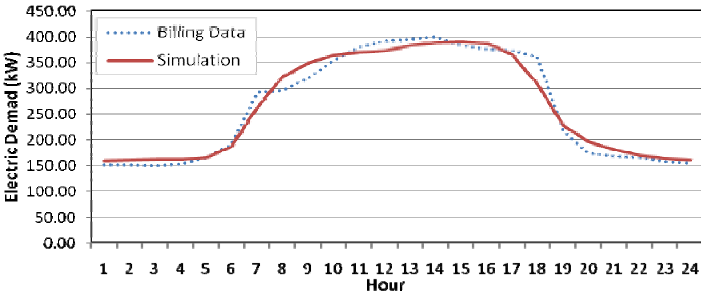

Fig.3. Annual Average Hourly Electrical Demand Profile

Once the hourly electric demand is calibrated, the next step is to calibrate electric energy consumption. The hourly profile provides a daily demand of the electricity, whereas the annual electric energy consumption gives the monthly profile of electricity consumption. Figure 4 presents the comparison of annual electric energy consumption between 2007 bills and the simulation results. On average, the simulation electric energy consumption agrees to the actual electric bills by 99%. This is a satisfied calibration. Next, simulation runs can be conducted.

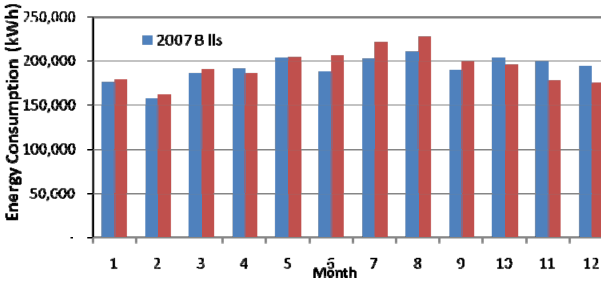

Fig.4. Annual Electrical Energy Consumption

3. Results and Discussion

(1) Simulation Tactics. The simulation of the simulation-assisted energy management and control system (SAEMCS) turns out to be a challenge because there is no available function in the DOE-2.2 software to simulate the energy management and control system. Instead, the SAEMCS was asking for creation of numerous temperature schedules and then running the DOE-2.2 simulation, and next choosing the temperature schedule that saves the most electricity for saving study. In order to demonstrate the savings from the SPEMS, a simplified approach was taken in the current research to mimic how the SAEMCS would control the indoor temperature. Twenty indoor temperature set point schedules were created based on the following three factors: outside weather condition, internal loads, and the productive workspace temperature. Multiple DOE-2.2 runs were then made and the schedule with the highest savings for every month was chosen to run for the saving study. The reason for choosing indoor temperature set point to set the schedule is that, in the DOE-2.2 simulation, indoor temperature set point controls the supply of cool air and it also directly controls the HVAC system run-time. One can lower the temperature set point to draw more cooling load inside such that it indirectly controls the chillers at any given time. Conversely, one can increase the indoor temperature to rest the chillers.

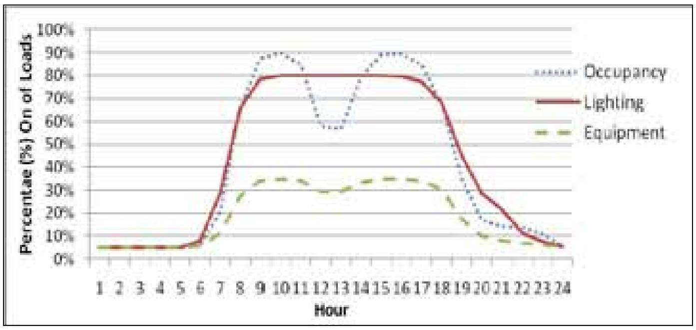

Fig.5. Hourly Weather Independent Internal Load Profile

When the indoor temperature set-point schedules were created, three energy savings strategies were applied. The first is to pre-cool running chillers during lunchtime (Noon to 1:00 pm) in order to reduce the chiller's runtime during the peak energy use time period. The second is to start temperature set back as the occupancy rates drop in the building. The last strategy is to slowly lower the temperature set-point in the morning until the occupant body temperatures reach the body comfort level of 98.6°F.

Figure 5 shows the hourly change of percentage-on of loads in occupancy rate, lighting use and demand of plug load (equipment). The lighting equipment tends to be powered on during entire business hour in an open office configuration because it is ineffective to install occupancy sensors on every lighting fixture in the open office space. Therefore, the energy management control system controls the light in the way as shown. It can been that as the occupancy rates fall, the equipment demand tends to fall as well since the office equipment is going into the idle mode. For example, copy machines goes to a sleep mode when they are not used for more than an hour. An automatic system like this can bring the plug load down during lunchtime.

Based on the 2007 NOAA San Jose weather record, an average outside wet bulb temperature plot was created and it is shown in Figure 6. It can be seen that three average hourly wet bulb profiles are displayed: January, July, and the annual average. It appears that the outdoor wet bulb temperature peaks at 1.00 p.m. Thus, the building can potentially save energy by reducing the cooling tower run-time during this hour. The January profile is a good representative of a winter wet bulb temperature profile whereas the July profile is a good representative of a summer wet bulb temperature profile. Note that, the outside wet bulb temperature is closely related to the cooling tower efficiency and it is advisable to run the tower when the wet bulb temperature is lower. As the outside wet bulb temperature increases, the cooling capacity on a cooling tower will fall. As a result, it will become more difficult to remove the heat using the evaporation of water.

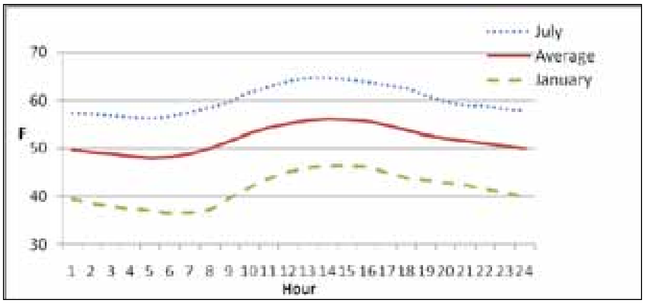

Fig.6. 2007 Hourly Outside Wet Bulb Temperature In San Jose

Starting at 5 p.m., employees begin to leave work and this can be observed in Figure 5 that the occupancy, lighting, and equipment loads all reduced after 5 p.m. At such a condition, the temperature set back strategy should be turned on in order to reduce the chiller run-time. If the SAEMCS predicts that there is a lower demand ahead, it will force the chillers to run at their highest efficiency even though the required cooling supply is lower. For example, if at 4:30 p.m. the internal set point temperature is at 74°F and the chillers need to run at 90% load to meet that cooling load. Then the SAEMCS can decide to run the chillers at 85% load because the chiller efficiency is higher at that load. As a result, it will produce enough cool air to keep the internal temperature at 75°F as it was scheduled.

It is worth to mention that the indoor temperature set point and body temperature together are an important factor for keeping employees productive and comfortable. In many studies of productivity at work, researchers found an inverted U-shape relationship centred between 72°F (22°C) and 77°F (25°C) [13]. As the indoor temperature deviating from that range, human work productivity would fall by 2% per every degree Celsius. It is safe to draw the conclusion that if the indoor temperature is set between 72°F to 77°F and then the SAEMCS can fluctuate within this temperature range without sacrificing human work productivity.

Besides the indoor temperature set point and body temperature, thermal comfort is another factor that is related to the human work productivity. The thermal comfort is achieved by maintaining body temperature of 98.6°F (typically between 98°F and 99°F). Whether the body feels comfortable or not depends on whether the body temperature is below or above the body temperature of 98.6°F. Body temperature varies throughout the day: it reaches its lowest point at 4 a.m. and its highest point between 4 p.m. to 6 p.m. Therefore, in the morning, the body temperature often is below the body temperature of 98.6°F and the person tends to prefer a warmer ambient temperature until their body temperature reaches the comfort level of 98.6°F. In the afternoon, the body temperature is well above the comfort temperature level of 98.6°F and the cooler ambient temperature makes people feel better as it helps the body to regulate its temperature.

(1) *Running the Simulation at Optimal Indoor Temperature Set Points.* Based on the three energy saving strategies: (1) to pre-cool running chillers during lunchtime (Noon to 1:00 pm), (2) to start temperature set back as the occupancy rates drop in the building, (3) to slowly lower the temperature set-point in the morning until the occupant body temperatures reach the comfort level of 98.6°F, twenty temperature schedules were created and compared against the baseline. Based on the independent DOE-2.2 runs of different temperature schedules, the SAEMCS would choose the "optimal" temperature schedule to run the building.

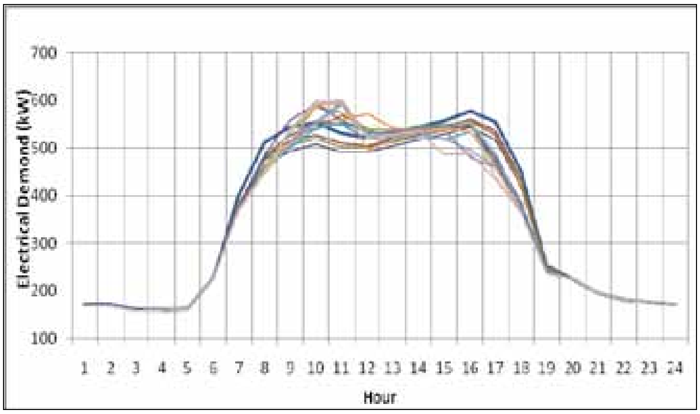

Fig.7. Electrical Demand Based on Different Temperature Set Point Schedules

Figure 7 shows hourly electric demand for a peak day in 2007. The different colour lines present different temperature schedules and thus they create different demand profiles during 24hr cycle. The peak day was defined by the California Public Utilities Commission (CPUC) and the hottest three consecutive weekdays in 2007 were July 17 to July 19. As shown, the peak demand appeared to occur between 10:00am to 11:00am. The second peak seemed to take place around 4:00p.m.

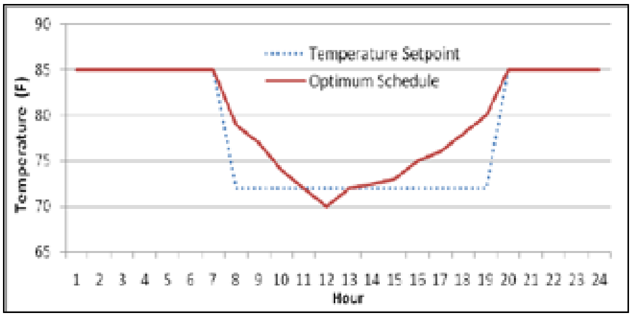

Fig.8. Comparison of Temperature Set Point Schedules

Figure 8 shows the difference between the baseline and optimal temperature set point schedules. The average indoor temperature set point for the July optimal schedule is 74.8°F during business hours but the average indoor temperature between 11 a.m. and 4 p.m. is 72.5°F. For the baseline schedule, the average indoor temperature is set constant at 72.5°F during the entire business hours.

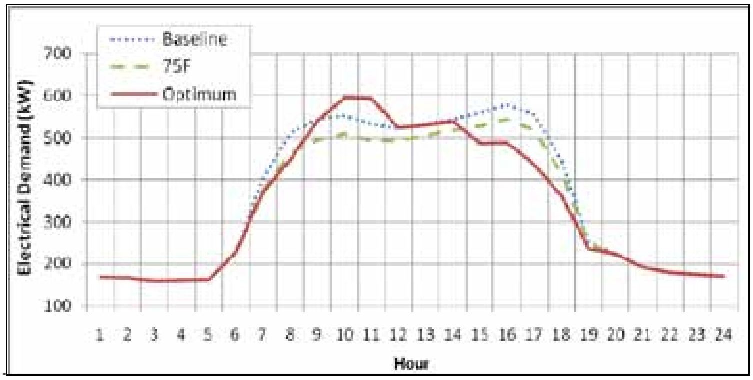

Fig.9. Comparison of Energy Demand Profile Among Different Set-Point Schedules

Finally, a comparison of hourly electrical demand profile is show in Figure 9 between the baseline schedule, the 75°F constant temperature set point schedule, and the July optimal schedule. By following the redline, it can be seen that, in the morning, the optimal temperature set point schedule demands less energy because the lower temperature set points is able to provide comfortable temperatures until the body temperature reaches its comfort level of 98.6°F. The cooling load then continues to increase throughout the morning to cool the building until noon time. From noon to 2 p.m., the energy demand stays almost constant as the pre-cool strategy pays off by slowly increasing the temperature set point. At 4 p.m., the SAEMCS anticipates the lower cooling demand after 5 p.m. and starts the set back process.

(2) *Cost Effectiveness Study.* The result of running the simulation - assisted energy management and control system (SAEMCS) on the building mode was calculated. The annual energy savings from the SAEMCS is 52,254.36 kWh, which is a 2.25% energy reduction. The building is in PG&E rate schedule E19S, which charges $0.15217 per kWh during the summer. The monetary annual savings is $7,951.55.

The estimated cost of implementing the SAEMCS is $90,480.00 for a 200,000 square foot office building. The cost breakdown is listed in Table 1. More sensors are required to be installed on-site to provide more feedback to the SAEMCS. In order to create a building model, a full building audit is needed. On top of the cost of implementing the SAEMCS, there is also the cost involved to commissioning the project, creating reports and user manuals, and training employees.

Table 1 Estimated Cost of the Project

Components	**Materia l ($)**	**Hours**	**Rate ($/hr)**	**T&M Cost ($)**
Integrated BAS/EMS	5,000	80	120	14,600
Sensor Installation	15,000	240	60	29,400
Building Audit	1,000	80	120	10,600
Computer Modeling		160	120	19,200
Commission		80	120	9,600
Report/ Manual	1,000	40	80	4,200
Training		24	120	2,880
Total Cost ($)				**90,480**

With the estimated cost of $90,480.00 to implement the SAEMCS for a 200,000 square foot office building, if the energy savings are $2Mwh, then the annual cost savings would be $7,952. The SAEMCS implementation will require 11.4 years to break even based on annual energy savings. The Database for Energy Efficiency Resources (DEER) estimates the expected useful life of typical HVAC equipment at 15 years and the SPEMS can break even before its predicted lifetime.

4. Conclusion

By running the simulation-assisted energy management and control system (SAEMCS) it resulted in a 2.25% energy reduction from the Legacy Civic Towers building. In 1988, Cumali group implemented simulation-powered EMCS' on three large office buildings and they were able to achieve a 20% energy reduction. The major source of this discrepancy is caused by the building code where whether a higher efficiency standard was enforced by the local government or not. A modern building, like Legacy Civic Towers, has better insulation, better glazing, more efficient office equipment, and more efficient HVAC components. Along with these technological improvements, the EMCS already optimized the system. As a result, savings from global optimization have diminished compared to Cumali's experiment in 1988.

The payback period for SPEMS is 11.4 years which makes it difficult to sell to customers because a payback period over 10 years is considered to be too long. The sophistication of the SPEMS implementation leaded to high cost as shown in cost effectiveness study. In order to market proliferate SPEMS, the payback period needs to be less than 3 years, and otherwise facility managers find it difficult to justify the project cost.

In the future, the SAEMCS should be able to communicate with local weather stations and the utility company's server to obtain current data. Employees in the building are recommended to have a radio frequency identification card so that the SAEMCS can monitor the building occupancy level and provide the feedback. Based on the building occupancy, the SPEMS the is able to shut down lights and plug loads in the vacant rooms to further reduce the cost during the time when the cooling load for next hour is being estimated. Another strategy is to consider using the building energy management system based on the ontology inference rules [14]. If all these capabilities are simulated, the savings would be large enough to be worth implementing the SAEMCS on all buildings.

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